XII International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS XII
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UNLOAING AND RE-LOADING FEATURES OF PRE-STRAINED STEEL AT LOW TEMPERATURE

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Key words: Elastic response, Plastic pre-strain, Unloading, Re-loading, Inverse loading, Spring back.

Summary *In the present work the response of medium carbon steel is investigated experimentally and information on the features of initial loading, unloading, re-loading and inverse loading processes is collected. The experiment is a simple tension and compression test using a round specimen and stress-strain curves are drawn after giving strain histories to specimens. The value of Young's modulus is measured from the stress-strain curve to evaluate the influence of pre-strain. Taking the result into consideration the intensity of predicted spring back of a thin sheet after bending process is evaluated.*

1 INTRODUCTION

Numerical analyses have been used as powerful assisting tools in many industries. Elastic-plastic finite element analysis is one of those tools. However it is said that there is often a discrepancy between the predicted and real product geometries. One of the reasons is the modeling of the material behaviour especially the elastic response after loading. Usually metallic materials are deemed a linear elastic bodies and the elastic constants are constant regardless of the plastic strain history. Namely the Young's modulus and Poisson's ratio remain constant after the materials undergo plastic strain history. However there are some research works in which it is stated that Young's modulus considerably decreases after small plastic deformation [1], [2]. Further research work to be carried out from now on is collecting quantitative data on the intensity of the decrease in Young's modulus because there is a discrepancy among the data in previous works. In addition the responses of unloading, re-loading and inverse loading processes must be separately collected for the modeling of material behaviour that more precisely predicts the geometry of products after processing processes. In the present paper consecutive tension and compression tests are carried out to grasp the basic responses of medium carbon steel, and a method is proposed to predict the final geometry of product taking an example of elastic-plastic bending process.

2 EXPERIMENT

The material adopted for the tension test is a medium carbon steel of which chemical compositions are shown in Table 1.

Table 1: Chemical compositions of material

C	Si	Mn	P	S
0.42～0.48	0.15～0.35	0.60～0.90	<0.030	<0.035

Fig.1 shows the outline of experiment. Parent steel bar was subjected to annealing process to follow the thermal history in Fig.1 and round specimens were manufactured by turning. Two strain gauges were placed at the centre prior to tension and compression tests. The tests were carried out in a framework to ensure a concentric testing of a specimen. After initial loading cycles of unloading and re-loading were repeated in a pitch of about 1% plastic strain until inverse loading was given to the specimen. The average value of the signals of two strain gauges was calculated to draw a stress-strain curve.

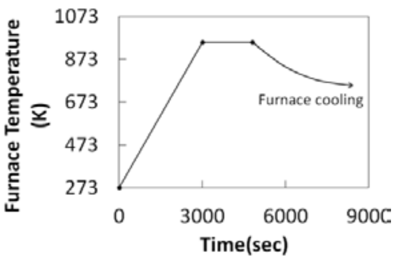


Figure 1a: Thermal history give to parent bar

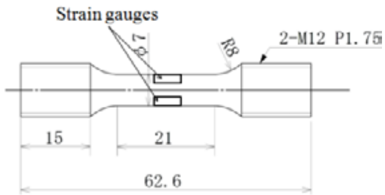


Figure 1b: Specimen geometry

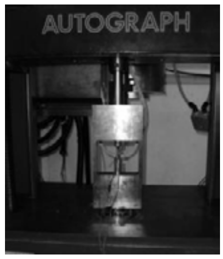
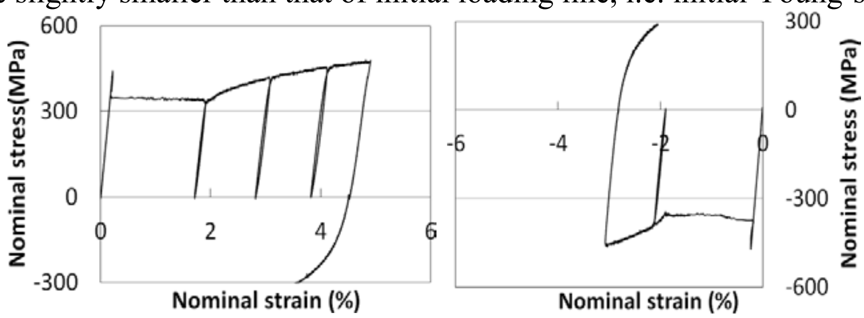


Figure 1c: View of testing

Figure 1: Experimental procedure

3 RESULTS

Examples of cycles of nominal stress and nominal strain history on tension side and compression side are shown in Fig.2. The unloading line and inverse loading line are not linear because of the influence of the Bauschinger's effect. The tangent of re-loading line seems to be slightly smaller than that of initial loading line, i.e. initial Young's modulus.



Tension side Compression side

Figure 2: Examples of nominal stress and strain history on tension and compression sides

As it is shown in Fig.3, initial loading curves on tension sides are point symmetric each other around the origin, and the material is deemed isotropic.

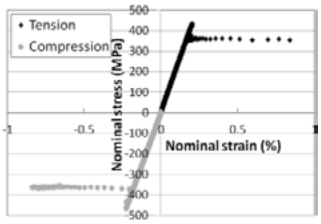


Figure 3a: Comparison of initial loading curves on tension and compression sides

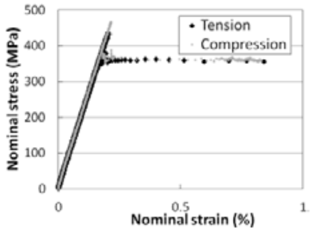


Figure 3b: Mapping of compression loading curve onto tension loading curve

Figure 3: Point symmetry of stress-strain curves on tension and compression sides

3.1 Method of data analysis

The loading curves of which examples were shown in the previous section are converted to true stress-true strain curves to carry out the following analysis. In addition, another data conversion is carried out to draw a local stress-strain curve in the vicinity of unloaded point. The reason for drawing two types of stress-strain curve is as follows. There are some research works in which it is stated that the Young's modulus considerably decreases in accordance with the progress of plastic deformation [1], [3], but there is another research work showing that transfer of the origin to the unloaded point to describe the local response of deformed material well simulates the spring back feature.

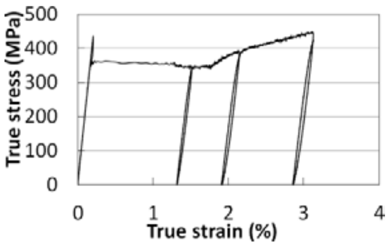


Figure 4a: Example of converted true stress-true strain curve

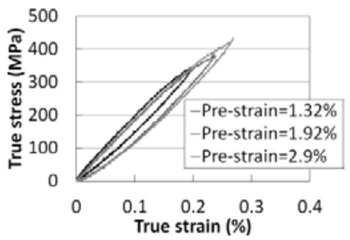


Figure 4b: Example of local stress-strain curve in the vicinity of unloaded point

Figure 4: Examples of two types of stress-strain curve

3.2 Unloading and inverse loading

Unloading feature is non-linear and it can be well approximated by equation (1) with a second order polynomial of strain defined around new origin of unloaded point as follows.

$$\sigma = a\varepsilon^2 + b\varepsilon \tag{1}$$

Figure 5 shows the dependency of coefficients a, b on the pre-strain. The values of a and b decrease with the increase of pre-strain, and converge to constant values at approximately 4% strain. Namely the response after 4% strain is the same. If one wants to estimate the Young's modulus in unloading from the tangent of the unloading curve, it is calculated by equation (2). The result calculated at the start point of unloading curve is shown in Fig.6.

Figure 5a: Influence of pre-strain on coefficient a **Figure 5b**: Influence of pre-strain on coefficient b

Figure 5: Influence of pre-strain on coefficients of unloading curve

$$\frac{\partial \sigma}{\partial \varepsilon} = 2a\varepsilon + b \tag{4}$$

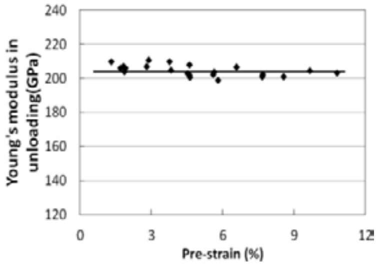


Figure 6: Influence of pre-strain on tangent at start point of unloading curve

Inverse loading curve may be approximated in a manner similar to that for unloading curve. Other curve fitting may be possible but it will be practical if the fitted curve of unloading process is applicable to the inverse loading process. In order to check the possibility the fitted curve for unloading process given by equation (1) was tried out on the inverse loading process. Fig.7 shows an example. Until the compressive strain reaches -0.35% the fitting is satisfactory. In a spring back phenomenon the strain increment on the inverse loading side may be small enough to apply the fitted curve on unloading process to inverse loading process.

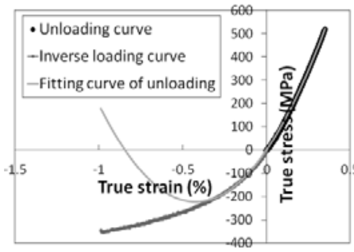


Figure 7: Applicability of fitted curve of unloading process to inverse loading process

3.3 Re-loading

The stress-strain relationship is well approximated by line fitting especially the stress is over 50MPa. The tangent of re-loading line is taken as the Young's modulus of the re-loading process. Fig.8 shows the influence of pre-strain on the Young's modulus of re-loading process. Starting from over 200Gpa Young' modulus decreases according to the increase in pre-strain until it saturates to 180Gpa after pre-strain reaches 4%. The reduction is about 10 to 15% and it is smaller than that in previous works. The reason is adoption of the local strain.

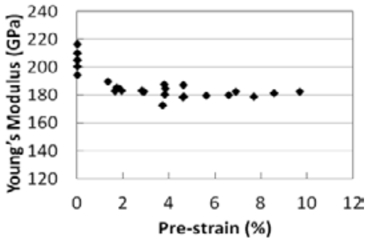


Figure 8: Influence of pre-strain on Young's modulus of re-loading process

4 DISCUSSION

Material temperature increases by plastic working, and it is important to evaluate the influence of temperature on the material responses after pre-strain. For this purpose other type of tension test was carried out at different temperatures up to 473K : room temperature, 348K, 373K, 398K, 423K, 448K and 473K. The range of temperature covers the peak temperature of material after ordinary cold plastic working. Specimen geometry is shown in Fig.9. The specimen has a pair of fins to hold an extensometer. The test was carried out in a furnace shown in Fig.10, and an extensometer was attached onto the fins.

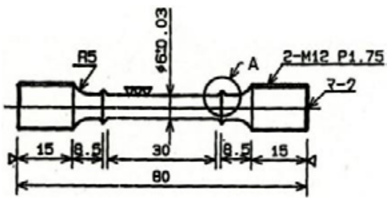


Figure 9: Geometry of specimen for tension test in furnace

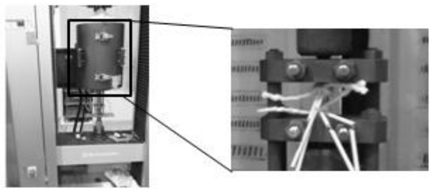


Figure 10: Furnace for testing and equipment for fixing extensometer onto fins

The results are shown in Figs.11 and 12. Fig.11 shows the influence of pre-strain on Young's modulus at room temperature, and present data is compared with the results in Fig.8. There is a good agreement between the two results. Fig.12 shows influence of temperature on Young's modulus. Although the initial Young's moduli are slightly smaller than those at room temperature the decreasing tendencies are similar to that at room temperature except those at 348K and 373K. Because the axial strain was calculated from the change in distance between two fins elastic-plastic FEA was carried out to check the uniformity of axial strain between two fins. An example is given in Fig.13. Although axial strain is small in the vicinity of fin the average axial strain between fins was almost equal to the strain in the parallel zone.

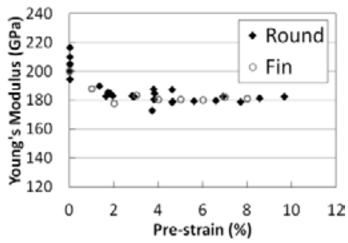


Figure 11: Comparison of changes in Young's modulus between JIS5 and fin specimen

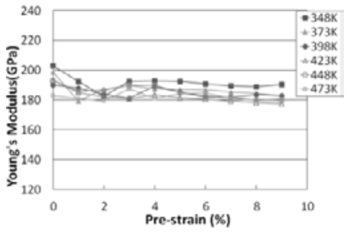


Figure 12: Influences of pre-strain and testing temperature on Young's modulus

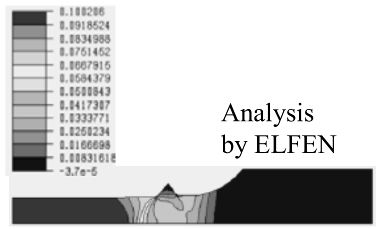


Figure 13: Example of FEA for checking uniformity of axial strain

5 APPLICATION

In order to examine the applicability of measured responses to metal working processes they were tried out on a roll-bending process is shown in Fig.14. The modeling follows the previous work [4].

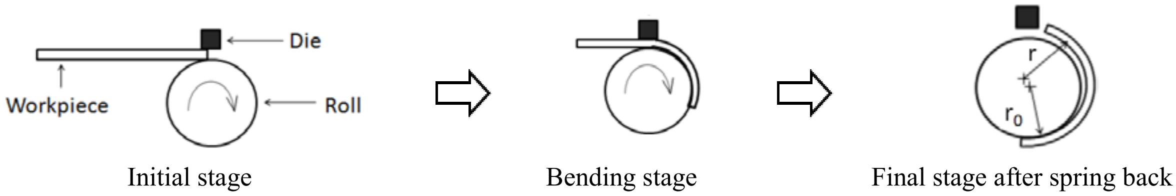


Figure 14: Outline of roll-bending process of sheet

Comparison of predicted results is given in Fig.15 between the material model using constant Young's modulus and that adopting changing responses. The spring back predicted by the latter is larger than that by the former and it explains the behaviour in spring back.

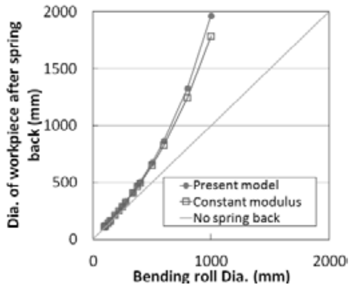


Figure 15: Comparison of spring back behaviour between two material models

6 CONCLUSIONS

Tension and compression tests were carried out to investigate the influence of pre-strain on the responses of unloading, inverse loading and re-loading processes. The unloading and inverse loading curves are well fitted by a second order polynomial of the local strain, and re-loading process is well approximated by a line. A material model considering these responses showed better prediction of spring back behaviour of a sheet after roll-bending.

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